DEVELOPMENT OF ULTRASONIC TOMOGRAPHY FOR COMPOSITION DETERMINATION OF WATER AND OIL FLOW

NG WEI NYAP

A thesis submitted in fulfilment of the
requirements for the award of the degree of
Master of Engineering (Electrical)

Faculty of Electrical Engineering
Universiti Teknologi Malaysia

OCTOBER 2005

To my dearest parents, Ng Siew Sui and Voon Moi Fah,
my dearest brothers and sister, my friends,
whoever help and support me in the thesis.

ACKNOWLEDGEMENT

First of all, I would like to express my gratitude to all those who give helps and support to me in doing this thesis. I wish to thank my supervisor, P.M. Dr Ruzairi Hj Abdul Rahim, for his advice, guidance and encouragement throughout the process of doing the project and writing this thesis.

Special thanks also to Mr. Chan Kok San for his advice and helps throughout the project.

Not forgetting, thanks to all my friends and staffs from Faculty of Electrical Engineering for their support and encouragement.

ABSTRACT

This project presents an implementation of the ultrasonic tomography to determine the composition of the water and oil flow. The transmission method of ultrasonic tomography is implemented in this project as the ultrasonic waves can propagate through both the medium of water and oil. This method is also one of the non-invasive methods that do not disturb the internal flow of the pipeline. The velocity of ultrasonic waves varies in water, oil and different composition of water and oil. The composition of water and oil can be determined from the measurement of this propagation time. Therefore, the design of the electronic circuits is to measure the propagation time of the ultrasonic waves through the medium. There are sixteen pairs of ultrasonic sensor mounted non-invasively around the periphery of an acrylic pipe. The grease is used as the coupling material to mount these ultrasonic sensors. The ultrasonic sensor used is 40 kHz of its frequency and 125^{o} of its beam angle. The beam angle of the ultrasonic sensor is preferred to be wider to provide wider visualization area. In this project, different composition of water and oil are used and the propagation times of the ultrasonic waves through the medium are then measured. These measurements are read into the computer through the data acquisition system (DAS) card. The cross-sectional-image is reconstructed by a custom-created software using Microsoft Visual Basic 6.0. The image reconstruction algorithm that used in the software is linear back projection (LBP) algorithm. The composition of the water and oil of the flow is determined from the reconstructed image. The composition of the water and oil will be shown in numerical forms and their distribution in the flow could be seen from the image. In this thesis, the results obtained from the project are presented. The implementation method, reconstructed images and analysis of the results are also presented in this thesis. This system can be implemented and bring benefits to the oil production industries.

ABSTRAK

Projek ini adalah berkaitan dengan penggunaan tomografi ultrasonik untuk mengukur komposisi air dan minyak dalam paip. Kaedah penghantaran tomografi ultrasonik digunakan dalam projek ini kerana gelombang ultrasonik boleh merambat melalui air dan minyak. Kaedah ini tidak memerlukan penebukan lubang dilakukan ke atas paip. Halaju gelombang ultrasonik adalah berlainan dalam air, minyak serta campuran air dan minyak yang berlainan komposisinya. Komposisi air dan minyak boleh diketahui dengan mengukur masa perambatan ini. Maka, rekaan litar elektronik adalah bertujuan untuk mengukur masa perambatan gelombang ultrasonik ini. Terdapat enam belas pasang sensor ultrasonik dilekat di sekeliling bahagian luar paip. Gris digunakan sebagai bahan pelekat di antara sensor ultrasonik dan permukaan paip. Frekuensi sensor ultrasonik yang digunakan adalah 40 kHz, dan sudut gelombangnya adalah 125^{o}. Sudut gelombang yang lebih luas membolehkan kawasan yang lebih luas dapat dikesan. Dalam projek ini, komposisi air dan minyak yang berlainan digunakan dan masa perambatan gelombang ultrasonik melaluinya diukur. Pengukuran ini dibaca ke dalam komputer dengan menggunakan kad DAS. Imej keratan rentas adalah dihasilkan dengan menggunakan perisian Microsoft Visual Basic 6.0. Algoritma yang digunakan untuk membina imej adalah algoritma ‘Linear Back Projection’. Komposisi air dan minyak adalah ditentukan daripada imej keratan rentas yang dihasilkan. Pengagihan air dan minyak dalam paip juga dapat diperhatikan daripada imej itu. Dalam tesis ini, keputusan yang diperolehi daripada projek ditunjukkan. Kaeadah pelaksanaan, imej keratan rentas yang dihasilkan dan analisis daripada keputusan juga dibincangkan dalam tesis ini. Sistem ini boleh dilaksanakan dan membawa faedah kepada industri pengeluaran minyak.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS / SYMBOLS

A	-	Attenuation of the ultrasound
A_V	-	Amplification gain of amplifier
c	-	Speed of ultrasound
CSV	-	Comma separated value
CT	-	Computed tomography
$D_{\max}(Tx, Rx)$	-	Maximum propagation time of ultrasound
$D_{\min}(Tx, Rx)$	-	Minimum propagation time of ultrasound
DAS	-	Data acquisition system
DDB	-	Device dependent bitmap
DIB	-	Device independent bitmap
$D_{LBP}(x, y)$	-	Concentration profile
DLL	-	Dynamic link libraries
e	-	Napier's constant, 2.71828
ECT	-	Electrical capacitance tomography
ECIO	-	External clock with I/O pins enabled
EIT	-	Electrical impedance tomography
f	-	Frequency of ultrasound
F_r	-	Repetition frequency of microcontroller
f/s	-	Frame per second
GHz	-	Gigahertz
GUI	-	Graphical user interface
Hz	-	Hertz
IC	-	Integrated circuit
IDE	-	Integrated Development Environment
i/o	-	Input and output pins
kHz	-	Kilohertz

km/s	-	Kilometer per second
LBP	-	Linear back projection
l/min	-	Liter per minute
MHz	-	Megahertz
mm	-	Millimeter
MOSFET	-	Metal-oxide-semiconductor field-effect-transistor
MRI	-	Magnetic resonance imaging
m/s	-	Meter per second
m/µs	-	Meter per microsecond
mm/µs	-	Millimeter per microsecond
NMR	-	Nuclear magnetic resonance
ns	-	Nanosecond
ρ	-	Density of materials
P_r	-	Reflection coefficient
P_t	-	Transmission coefficient
PCB	-	Printed circuit board
PCI	-	Peripheral Component Interconnect
PET	-	Positron emission tomography
PVC	-	Polyvinyl chloride
RAM	-	Random Access Memory
Rx	-	Receiver
$S_{Tx,Rx}$	-	Signal loss or difference of propagation time
SNR	-	Signal to noise ratio
T	-	Period of ultrasound
T_{cy}	-	Instruction cycle
T_r	-	Time resolution of binary counter
Tx	-	Transmitter
TOF	-	Time of flight
$Total_C$	-	Total concentration
µs	-	Microsecond
V	-	Volt(s)
V_{p-p}.	-	Peak to peak voltage

Win32 API	-	Microsoft® 32 bit Windows™ Application Programming Interface
z	-	Acoustic impedance
α	-	Attenuation coefficient
ε	-	Permittivity
λ	-	Wavelength of ultrasound
ΔD	-	Difference of the propagation time
$<$	-	Less than

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 An Overview of Process Tomography

Tomography can be defined as making cross-sectional images of an object, as the Greek word ‘tomos’ means ‘to slice’ and ‘graph’ means ‘image’ (William and Beck, 1995). A cross-sectional image of the object monitored is called a tomogram, while the equipment that generates the image is a tomography. Process tomography is analogous to the application of medical tomographic scanners that examine the human body, but is applied at industries to examine the industrial process such as pipelines, stirred reactors, fluidized beds, mixers and separators.

The tomographic imaging is first used in medical field, which is then applied in the industrial processes. A number of applications of tomographic imaging of process equipment were described in the 1970s but generally these involved using ionizing radiation from X-ray or isotope sources (Plaskowski *et al.*, 1995). However, these were not satisfactory because of the high cost and safety constraints. These radiation-based methods also used long exposure times which meant that dynamic measurement of the real-time behavior of flow inside pipelines and process systems were not feasible. The equipment of the tomography for the industrial application must also be relatively low cost and able to make measurements rapidly.

In the mid-1980s, there were works started that led to the present generation of process tomography systems. A project on electrical capacitance tomography (ECT) for imaging multi-components flow from oil wells and pneumatic conveyors was carried out at the University of Manchester Institute of Science and Technology (UMIST) in England (William and Beck, 1995). About the same time, a group at the Morgantown Energy Technology Center in the USA was designing a capacitance tomography system for measuring the void distribution in gas fluidized beds (William and Beck, 1995). Hoyle and Xu (1995) had carried out a research about the design and application of ultrasonic sensor in tomography. Since then, there were many researches about tomography for the industrial and medical applications carried out in the United Kingdom (UK) and United States of America (USA).

Until today, there are many researches about tomography carried out at universities worldwide such as University of Leeds (UK), University of Aberdeen (UK), University of Pittsburgh (US), University of Melbourne (Australia), Universiti Teknologi Malaysia and Universiti Sains Malaysia. Besides this, there are companies that develop and sell commercial tomographic products. Process Tomography Limited (PTL) is one of the companies that have been supplying electrical capacitance tomography (ECT) imaging system since 1994. Its partner company, Tomoflow Ltd was established in 2001 to develop commercial tomographic multiphase flow meters. There are also many international symposiums, seminars and world congress on tomography held every year that attract the participation of many researchers.

1.2 Background Problems

In the 1990s, industry is under pressure to utilize resources more efficiently, and to satisfy demand and legislation for product quality and reduced environmental emissions (Plaskowski *et al.*, 1995). Since then, there is a need for a monitoring instrument that could monitor the industrial processes and provide information to improve yields, quality, efficiency and overall control of the processes. Often, this must be done non-invasively by tomographic instruments because the conventional measuring instrument maybe unsuitable to be exposed to the harsh internal condition of the pipe or by their presence, the flow inside the pipes is interrupted.

In ultrasonic tomography, several researches have been done on gas and liquid two phase flow regime. Xu *et al.* (1997) had implemented a gas and liquid two phase flow regime system by using ultrasonic tomography. The system was based on a binary logic algorithm and a method of time-of-propagation along straight path. Yang *et al.* (1999) had presented a paper on real-time ultrasonic tomography for two phase flow imaging using a reduced number of transducers. The system employed a relatively small number of transducers that produced fan-shaped beam profile to effectively visualize the cross-sectional of the pipe. A better reconstruction quality was achieved by combining the transmission and reflection mode of ultrasound. An investigation on cross-sectional distributions of gas and solid holdups in slurry bubble column using ultrasonic tomography was carried out by Warsito *et al.* (1999). The results showed the time-averaged cross-sectional distribution of gas and solid holdups in slurry bubble column.

At Universiti Teknologi Malaysia, Khor (2002) had done project on comparison between air and liquid using ultrasonic sensor in process tomography. Mohd Hafiz (2003) had implemented water and particles flow system using transmission mode of ultrasonic tomography. The attenuation of the ultrasound was taken as the measurements to reconstruct the cross-sectional image. No ultrasonic tomography system for the imaging of two liquids such as water and oil has been studied so far.

In optical tomography, Sallehuddin (2000) has used optical fibers for measurement of gas bubbles in a vertical water column. Sallehuddin (2000) showed that optical fibers are capable of making concentration measurements of small bubbles of diameter 1 to 10 mm in water with volumetric flow rates up to 1 l/min, and large bubbles of diameter 15 to 20 mm in water with volumetric flow rates up to 3 l/min on a hydraulic conveyor. However, if optical tomography is to be applied, the material of the pipe should be transparent or holes should be made around the pipe to accommodate the optical sensors so that the optical beam could penetrate through the flow. At Universiti Teknologi Malaysia (UTM), the invasive optical tomography system developed by Chan (2002) and Pang (2004) are intended for imaging solid particles in the air.

1.3 Problem Statements

The oil industries today such as cooking oil and palm oil industries face the problem to monitor the efficiency of their oil production. A monitoring system which can be applied non-invasively is much needed to monitor their oil production. Besides, the monitoring system should be able to provide the information about the composition of the oil. The composition of water that is mixed in the oil should be computed to find the efficiency of the oil production. In this situation, tomography is the technology that can be applied to solve the problem.

The major target of this project is to implement a monitoring system for water and oil flow using ultrasonic tomography. The system must able to provide information about the composition profile of the water and oil as well as the cross-sectional image of the flow. Studies need to be carried out, which included the hardware's fixture design, mounting technique, transmitter circuit design, receiver circuit design, hardware interfacing, image reconstruction algorithm and software programming.

1.4 Importance of Study

The ultrasonic tomography is one of the non-invasive techniques that can be used in the industry for monitoring the flow composition of two liquids flow such as water and oil. The non-invasive method provides the ultrasonic tomography with easy installation and portable convenience. The ultrasonic sensors are very easy to be mounted around the pipeline compared with other sensors. The installation of the ultrasonic tomography system also does not require the shut down of the industry's process. Moreover, this monitoring system does not disturb the internal flow of the pipe. All this benefits support the ultrasonic tomography to be chosen over the other invasive system. It is obvious that the ultrasonic tomography of this research has the potential to contribute to the cooking oil, palm oil and petroleum industries. In this case, the ultrasonic tomography can be applied to determine the composition of the water and oil for the palm oil and the petroleum.

There are several inventions using the ultrasonic techniques for determining the fluid composition that have already obtained the United States Patent such as U.S. Patent 5,473,934 by Cobb (1995), U.S. Patent 4,059,987 by Dowling *et al.* (1977) and U.S. Patent 4,656,869 by Zacharias (1987). However, those inventions required fluid samples taken from the pipelines or predetermined reference data saved in computer. Some of the inventions also used invasive techniques. Most obviously, those inventions did not display the cross-sectional image showing the composition of the fluid because they were not tomography systems. One of the inventions for monitoring the fluid composition is by Cobb (1995) using ultrasonic non-intrusive technique. Cobb (1995)'s invention involved measurements from the fluid, by which the fluid composition was then determined based on the calibrated data from analytical measurements of fluid samples. Another invention by Urmson *et al.* (1991) was an apparatus for determining the composition of fluid mixture by comparing acoustic travel-time of both changing and reference fluid samples. Invention by Tavlarides *et al.* (1989) was for measuring fractional volumetric holdup in a two liquids phase based on the acoustic velocities. Zacharias (1987) in his invention described a method of measuring the amount of water in crude oil pipeline by extracting a sample from the pipeline. Inventions by Smith (1985) and Dowling *et al.* (1977) were also used for determining the fluid composition that based on measurements of acoustic velocity. In short, those inventions used the same ultrasonic sensors as the ultrasonic tomography system, but the ultrasonic tomography system can display cross-sectional images of the pipeline in real time, determine the fluid composition based on concentration profile, required no samples taken from the fluids and non-invasive.

1.5 Research Objectives

The primary objective of this project is to determine the concentration of water and oil flow using ultrasonic tomography. The system must also provide the information about the concentration and display the cross-sectional image of the pipe in real time. The research objectives cover the development of sensor's fixture, excitation circuits, and signal conditioning circuits, hardware interfacing and development of software using Microsoft Visual Basic 6.0. The summary of the objectives of this project are listed as follows:

(i) To determine the composition of water and oil flow by implementing the transmission mode of ultrasonic tomography.
(ii) To study the characteristic of ultrasound and make use of it in monitoring the process of water and oil flow.
(iii) To search material for ultrasonic sensors and its hardware fabrication.
(iv) To design and implement signal conditioning circuits that can measure the time of flight (TOF) of ultrasonic wave and process the signals.
(v) To use the microcontroller as the switching device to control the signal generator, signal conditioning circuits and the data acquisition system (DAS) card.
(vi) To implement the principle of flow imaging by creating a custom software using Microsoft Visual Basic 6.0 that can provide information about the concentration of the water and oil flow.

1.6 Research Scopes

This project can be divided into a few parts such as sensor's fixture design, transmitter and receiver circuits design, hardware interfacing, switching control using microcontroller and software development. Figure 1.1 depicts the scope of this project.

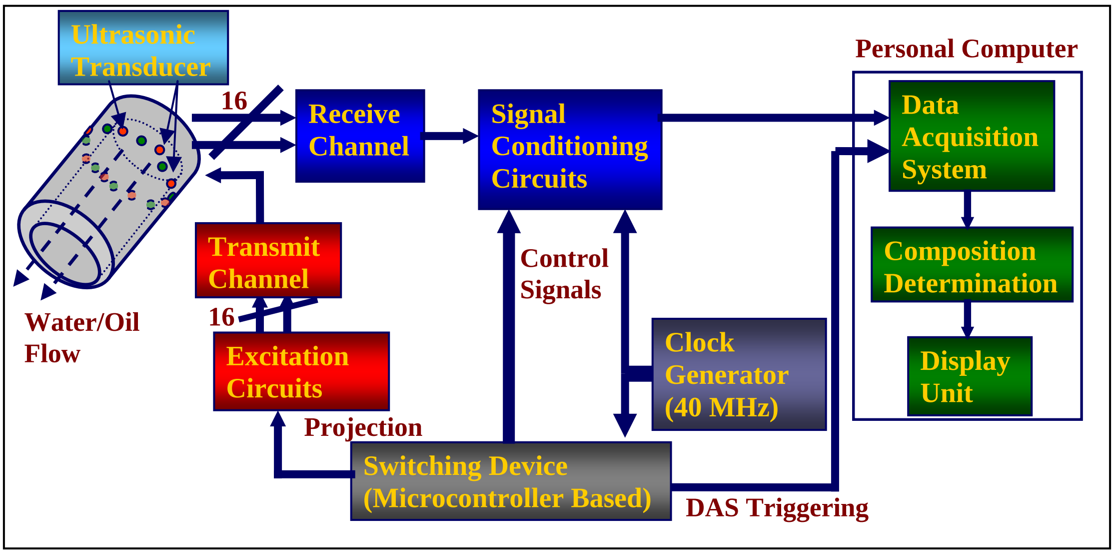

Figure 1.1: Scope of the Project

(i) Sensor's fixture design

The design of the sensor's fixture involves mechanical parts design with consideration to the sensor's physical parameter, sensor's placement geometry, mounting technique and the cost. Studies need to be done on mechanical drawing, mounting technique, type of sensor, material of pipe and cost of the fixture.

(ii) Transmitter and receiver circuits design

The transmitter circuit consists of excitation circuits that provide pulses to the ultrasonic sensors to transmit ultrasonic waves while the receiver circuit is to receive and measure the propagation time of the ultrasonic waves. The circuit implementation involves selection of electronic components, design and fabrication of circuits into printed circuit board (PCB), noise reduction and consideration of signals interfacing with the data acquisition system. The design of the signal conditioning circuit involves an amplifier circuit to amplify the received signal, a zero-crossing detector to detect the first arriving signal, a signal holding circuit to hold the first signal from the zero-crossing detector and a binary counter to measure the propagation time. Figure 1.2 below shows the layout design of the signal conditioning circuits.

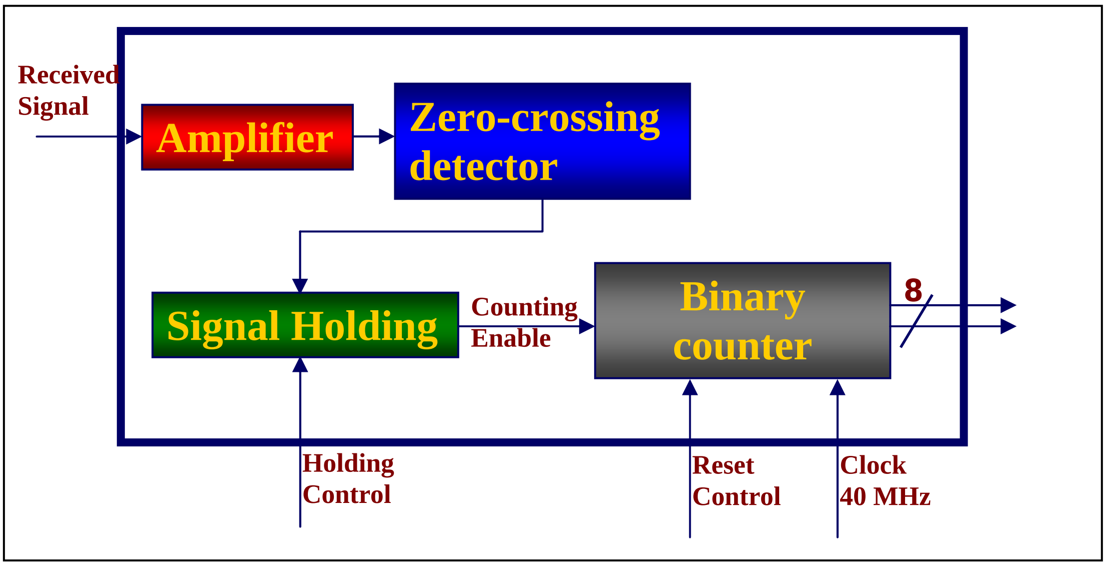

Figure 1.2: Layout of Signal Conditioning Circuit

(iii) Switching control using microcontroller

The microcontroller is used for timing control purpose to control the excitation circuits, signal holding circuits and data sampling of the data acquisition system (DAS) card. Handshaking is established between the hardware system and the computer by the microcontroller. Programming of the microcontroller involves accurate timing calculation so as to provide the control signals at the right time.

(iv) Hardware interfacing

The hardware interfacing is implemented by using a data acquisition system (DAS) card. Before doing the interfacing, the input range of the signals, method to trigger the DAS, method of sampling measurements, setup and configuration of the DAS in the computer need to be taken into consideration. 128 signals from the 16 binary counters should be sampled into the computer at one time. Checking must be done to make sure that the sampled measurements by using the DAS are correct.

(v) Software development

Software development includes the graphical user interface (GUI) design using Microsoft Visual Basic 6.0, implementation of image reconstruction algorithm, tomogram drawing, DAS configuration and operation, sensor modeling, sensitivity maps finding, solution of forward problem and data transferring. When writing the software, consideration is given to make sure that better performance and faster speed are achieved. The purpose of the software development is of course is to obtain the concentration profile and cross-sectional image of the water and oil flow. Visual Basic 6.0 is chosen because it is easier to learn Visual Basic 6.0 than other programming languages such as Visual C++ 6.0. A lot of resources about Visual Basic 6.0 can also be found from the internet.

1.7 Thesis Structures

Chapter I of the thesis presents an overview of process tomography, background problems that lead to the implementation of this research and problem statements that this research is going to solve. The importance of this study, research objectives and scope of the research is also included.

Chapter II provides more introductions to process tomography system, type of tomography sensors and several measurement methods of component concentrations.

Chapter III introduces more on ultrasound, several wave propagation methods of ultrasound and sensing modes of ultrasonic tomography.

Chapter IV describes the sensor modeling, sensitivity maps computation, computer interfacing using DAS card and hardware design of the ultrasonic tomography system. The purpose of the sensor modeling is to solve the forward problem and to compute the sensitivity maps. The design of the transmitter and receiver circuits will be described in details in this chapter.

Chapter V describes the implementation of the image reconstruction algorithm, composition determination based on concentration profile, operation of the DAS card, software development, programming structure and techniques as well as flow simulation program for several flow models.

Chapter VI includes all the results obtained from the experiments and the results' analysis. The error of the measurements and performance of the flow monitoring system will be found out. Comparison between the results obtained from experiments and results obtained from the flow model is also shown in this chapter.

Chapter VII is written to discuss the conclusion and important contributions from this research and suggestion for the future work.

REFERENCES

Barshan, B (2000). "Fast Processing Techniques for Accurate Ultrasonic Range Measurements." *Meas. Sci. Technol.*, Vol. 11, 45-50.

Bidin, A.R., Green, R.G., Shackleton, M.E., Stott, A.L. and Taylor, R.W. (1995). "Electrodynamic Sensors for Process Tomography." In Williams, R.A. and Beck, M.S. (1995). *"Process Tomography - Principles, Techniques and Application."* Jordan Hill: Butterworth Heinemann Ltd. 101-117.

Blitz, J. (1967). *"Fundamentals of Ultrasonics."* 2nd ed. Butterworth: Butterworth & Co (Publishers) Ltd.

Blitz, J. (1971). *"Ultrasonics: Methods and Applications."* Butterworth: Butterworth & Co (Publishers) Ltd.

Boylestad, R.L. and Nashelsky, L. (1999). *"Electronic Devices and Circuit Theory."* 7th ed. United States of America: Prentice Hall Inc.

Bray, D.E. and McBride D. (1992). "Nondestructive Testing Techniques." United States of America: John Wiley & Sons.

Brown, G.J., Reilly, D. and Mills, D. (1996). "Development of an Ultrasonic Tomography System for Application in Pneumatic Conveying." *Meas. Sci. Technol.*, Vol. 7, 396-405.

Buchanan, W. (1999). *"PC Interfacing, Communications and Windows Programming."* Great Britain: Addison-Wesley.

Chan Kok San (2001). *"Image Reconstruction for Optical Tomography."* Universiti Teknologi Malaysia: B.Sc. Thesis.

Chan Kok San (2002). *"Real Time Image Reconstruction for Fan Beam Optical Tomography System."* Universiti Teknologi Malaysia: M.Sc. Thesis.

Cheeke, J.D.N. (2002). *"Fundamentals and Applications of Ultrasonic Waves."* United States of America: CRC Press LLC.

Cobb, W. (1995). *"Ultrasonic Fluid Composition Monitor."* (U.S. Patent 5,473,934).

Deitel, H.M., Deitel, P.J. and Nieto, T.R. (1999). *"Visual Basic 6.0 – How to Program."* New Jersey: Prentice Hall.

Dowling, D.J., and Schoen, W. (1977). *"Apparatus and Method for Measuring the Water Content of Oil Flowing in a Pipe."* (U.S. Patent 4,059,987).

Floyd, T.L. (2000). *"Digital Fundamentals."* 7th ed. Upper Saddle River, New Jersey: Prentice Hall Inc.

Gamio, J.C. and Ortiz-Aleman, C. (2003). "An Interpretation of the Linear Back Projection Algorithm used in Capacitance Tomography." *3rd World Congress on Industrial Process Tomography*. Canada: The Virtual Centre for Industrial Process Tomography. 427-432.

Gooberman, G. L. (1968). *"Ultrasonics – Theory and Application."* London: The English Universities Press Ltd.

Hall, I.D., McNab, A. and Hayward, G. (1999). "Improved Ultrasonic Image Generation through Tomographic Image Fusion." *Ultrasonics,* Elsevier, Vol. 37, No. 433-443.

Halmshaw, R. (1993). *"Non-Destructive Testing."* 2nd ed. Great Britain: Edward Arnold, Hodder & Stoughton Ltd.

Holstein, P., Raabe, A., Muller, R., Barth, M., Mackenzia, D. and Starke, E. (2004). "Acoustic Tomography on the Basis of Travel-time Measurement." *Meas. Sci. Technol.*, Vol. 15, 1420-1428.

Hoyle, B.S. (1996). "Process Tomography using Ultrasonic Sensor." *Meas. Sci. Technol.*, Vol. 7, 272-280.

Hoyle, B.S., Xu, L.A. (1995). "Ultrasonic Sensors." In Williams, R.A. and Beck, M.S. (1995). *"Process Tomography - Principles, Techniques and Application."* Jordan Hill: Butterworth Heinemann Ltd. 119-149.

Hull, J.B. and John, V.B. (1988). *"Non-destructive Testing."* Hampshire: Macmillan Education Ltd.

ICP DAS Co. (2003). *"PIO-D144/D168A – User's Manual."* Taiwan: ICP DAS Co. Ltd..

Ingleby, P. and Wright, W.M.D. (2002). "Ultrasonic Imaging in Air using Fan-beam Tomography and Electrostatic Transducers." *Ultrasonics,* Elsevier, Vol. 40, 507-511.

Kak, A.C. and Slaney, M. (1988). *"Principles of Computerized Tomographic Imaging."* USA: IEEE Press.

Khor Kah Yen (2002). *"Comparison between Air and Liquid using Ultrasonic Sensor in Process Tomography."* Universiti Teknologi Malaysia: B.Sc. Thesis.

Kinsler, L.E., Frey, A.R., Coppens, A.B. and Sanders, J.V. (1982). *"Fundamentals of Acoustics."* 3rd ed. Singapore: John Wiley & Sons.

Krautkramer, J. and Krautkramer, H. (1983). *"Ultrasonic Testing of Materials."* 3rd ed. New York: Springer-Verlag.

Li, W. and Hoyle, B.S. (1997). "Ultrasonic Process Tomography using Multiple Active Sensors for Maximum Real-time Performance." *Chemical Engineering Science*, Vol. 52, No. 13, 2161-2170.

Malyarenko, E.V. and Hinders, M.K. (2001). "Ultrasonic Lamb Wave Diffraction Tomography." *Ultrasonics,* Elsevier, Vol. 39, 269-281.

McKee, S.L. (1995). "Applications of Nuclear Magnetic Resonance Tomography." In Williams, R.A. and Beck, M.S. (1995). *"Process Tomography - Principles, Techniques and Application."* Jordan Hill: Butterworth Heinemann Ltd. 539-548.

Microchip (2000). *"Analog / Interface Handbook."* United States of America: Microchip Technology Inc.

Microchip (2001). *"PIC16F87X Data Sheet."* United States of America: Microchip Technology Inc.

Mohd. Hafiz bin Fazalul Rahiman (2003). *"Image Reconstruction using Transmission Mode of Ultrasonic Tomography in Water-particles Flow."* Universiti Teknologi Malaysia: B.Sc. Thesis.

Mohd. Hezri bin Fazalul Rahiman (2002). *"Real-time Velocity Profile Generation of Powder Conveying using Electrical Charge Tomography."* Universiti Teknologi Malaysia: M.Sc. Thesis.

Myers, P.E., Beesley, M. and Martin, P.D. (1994). "Ultrasound Imaging In Large Gas and Liquid Processing Vessels." *ECAPT'94*, 354-358.

Naidu, P.S., Vasuki, A., Satyamurthy, P. and Anand, L. (1995). "Diffraction Tomographic Imaging with a Circular Array." *IEEE Transactions on Ultrasonic, Ferroelectrics and Frequency Control,* July 1995: IEEE, Vol. 42, No. 4.

Opielinski, K.J. and Gudra, T. (2000). "Ultrasound Transmission Tomography Image Distortions caused by the Refraction Effect." *Elsevier*, Vol. 38, 424-429.

Pang Jon Fea (2004). *"Real-time Velocity and Mass Flow Rate Measurement using Optical Tomography."* Universiti Teknologi Malaysia: M.Sc. Thesis.

Perry, G. (1998). *"Sams Teach Yourself Visual Basic 6.0 in 21 Days."* Indianapolis: Macmillan Computer Publishing.

Pintavirooj, C., Romputtal, A., Ngamlamiad, A., Withayachumnankul, W. and Hamamoto, K. (2003). "Ultrasonic Refractive Index Tomography." *Journal of WSCG*, Vol. 12, No.1-3.

Plaskowski, A., Beck, M.S., Thorn, R. and Dyaskowki, T. (1995). *"Imaging Industrial Flows - Application of Electrical Process Tomography."* Institute of Physics Publishing Bristol and Philadelphia.

Rozenberg, L. D. (1973). *"Physical Principles of Ultrasonic Technology."* New York: Plenum Press.

Ruzairi Abdul Rahim (1996). *"A Tomography Imaging System for Pneumatic Conveyors using Optical Fibers."* Sheffield Hallam University: Ph.D. Thesis.

Sallehuddin Ibrahim (2000). *"Measurements of Gas Bubbles in a Vertical Water Column using Optical Tomography."* Sheffield Hallam University: Ph.D. Thesis.

Sanderson, M.L. and Yeung, H. (2002). "Guidelines for the Use of Ultrasonic Non-invasive Metering Techniques." *Flow Measurement and Instrumentation*, Elsevier, Vol. 13, No. 125-142.

Schlaberg, H.I., Yang, M., Hoyle, B.S., Beck, M.S. and Lenn, C. (1997). "Wide-angle Transducers for Real-time Ultrasonic Process Tomography Imaging Applications." *Ultrasonics*, Elsevier, Vol. 35, No. 213-221.

Smith, G.E., (1985). *"Ultrasonic Densitometer for Liquid Slurries."* (U.S. Patent 4,522,068).

Stamnes, J.J. and Wedberg, T.C. (1994). "Diffraction Tomography Applications in Geophysics, Ultrasonics and Optics." *ECAPT'94*, 244-255.

Szilard, J. (1982). *"Ultrasonic Testing - Non-conventional Testing Techniques."* New York: John Wiley & Sons.

Tavlarides, L.L., and Bonnet, J.C. (1989). *"Self-Calibrating Ultrasonic Measurement of Dispersed Phase Volumetric Holdup in Liquid/Liquid Dispersions."* (U.S. Patent 4,852,396).

Urmson, J., Pearson, A. and Gidwani, S. (1991). *"Method and Apparatus for Fluid Mixture Monitoring, Constituent Analysis and Composition Control."* (U.S. Patent 5,060,507).

Warsito, Ohkawa, M., Kawata N. and Uchida S. (1999). "Cross-sectional Distributions of Gas and Solid Holdups in Slurry Bubble Column Investigated by Ultrasonic Computed Tomography." *Chemical Engineering Science*, Vol. 54, 4711-4728.

Williams, R.A. and Beck, M.S. (1995). *"Process Tomography - Principles, Techniques and Application."* Jordan Hill: Butterworth Heinemann Ltd.

Wojnar, L. (1999). *"Image Analysis: Application in Materials Engineering."* United States of America: CRC Press LLC.

Xie, C.G. (1995). "Image Reconstruction." In Williams, R.A. and Beck, M.S. (1995). *"Process Tomography - Principles, Techniques and Application."* Jordan Hill: Butterworth Heinemann Ltd. 281-323.

Xu, L.J. and Xu, L.A. (1997). "Ultrasound Tomography System used for Monitoring Bubbly Gas/Liquid Two Phase Flow." *IEEE Transactions on Ultrasonic, Ferroelectrics and Frequency Control,* January 1997: IEEE, Vol. 44, No. 1.

Xu, L.J., Han, Y.T., Xu, L.A. and Yang J.S. (1997). "Application of Ultrasonic Tomography to Monitoring Gas/Liquid Flow." *Chemical Engineering Science,* Vol. 52, No. 13.

Yang, M., Schlaberg, H.I., Hoyle, B.S., Beck, M.S. and Lenn, C. (1999). "Real-time Ultrasound Process Tomography for Two-phase Flow Imaging using a Reduced Number of Transducers." *IEEE Transactions on Ultrasonic, Ferroelectrics and Frequency Control,* May 1999: IEEE, Vol. 46, No. 3.

Zacharias, E.M. (1987). *"Method of Measuring the Amount of Water Flowing in a Crude Oil Pipeline."* (U.S. Patent 4,656,869).